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FABRICATION OF CUSTOMIZED DIE INSERTS USING CLOSED-LOOP DIRECT METAL DEPOSITION (DMD^{tm})

REFERENCE TO RELATED APPLICATION

This application claims priority from U.S. Provisional Patent Application Serial No. 60/399,264, filed July 29, 2002, the entire content of which is incorporated herein by reference.

FIELD OF THE INVENTION

This invention relates generally to additive manufacturing and, in particular, to the use of closed-loop direct-metal deposition (DMD) to fabricate customized die inserts.

BACKGROUND OF THE INVENTION

The desired function of dies, molds and three-dimensional components depends on the service conditions and the application. Often many of these three-dimensional components are expensive but rendered obsolete due to modest changes in dimension and/or operating conditions.

For metal die casting, especially aluminum die casting, traditional tool steels such as H13 get dissolved and this changes dimensions often after few thousand cycles. Coating of the surface may prevent or slow down the dissolution, but the coating spills off relatively easily under severe working environments.

In addition, stamping and injection molding and die casting dies often require modest changes during the design process for improved aerodynamics, last-minute engineering functional changes, or aesthetics of the product.

Direct-metal deposition (DMD^{tm}) may be used to achieve such objectives. The closed-loop DMD process (CLDMD) utilizes a patented optical feedback loop to maintain exacting tolerances, currently within 25micron to 150micron (J.Koch and J.Mazumder, Apparatus and Methods for Monitoring and Controlling Multi-Layer

Cladding, U.S. Patent No. 6,122,564, the entire content of which is incorporated herein by reference). Material can be delivered at the laser-melted pool by various means, including pneumatic powder delivery, wire feed or tape feed.

Either same material as the substrate or any other metallurgically compatible material can be deposited by this process. Through proper selection of the deposited material properties can be tailored to application requirement in addition to the geometric requirements. Surface oxidation during the process is minimized by inert shielding gas delivered either through the concentric nozzle or separate shielding nozzle. Under special circumstances, the process may be carried out in an inert atmosphere chamber.

A complex shape is generated by delivering desired alloy powder or wire on to the laser melted pool and changing the relative position of the laser beam and the substrate. The following relative movements can be utilized.

1) Stationary beam and material delivery (powder, wire feed, etc.) system and moving substrate,

2) Stationary substrate and moving beam and material delivery (powder, wire feed, etc.) system,

3) Stationary substrate and robotic embodiment of the moving beam and material delivery (powder, wire feed, etc.) system, and

4) Multiple laser beam systems for simultaneous deposition onto a die surface using the system 1 and or 3 above.

The capability of CLDMD can be utilized for improved thermal management of a tool. For example, conductive material such as copper can be incorporated inside a tool at critical points for use as a heat sink. Secondly, a conformal cooling channel can be incorporated within the die leading to improved heat extraction during service compared to presently used straight-line cooling channels in injection molding dies. Thirdly, pressure and temperature sensors can also be incorporated within the tool during CLDMD process, which impart thermal management. Improved thermal management

reduces the cycle time of an injection mold or a die cast mold leading to substantial cost savings.

SUMMARY OF THE INVENTION

According to the invention, techniques such as closed-loop direct metal deposition (CLDMD) and laser cladding are used to design and tailor tools and components for specific applications. Closed loop DMD in particular can achieve such changes on an existing tool with proper alloy matching (often referred as color matching in the die repair industry) and close dimensional tolerances. This process leads to cost and lead-time savings by reducing post processing cost and reconfiguring the original tool.

Surface properties of die casting dies often requires hard materials with low solubility in the casting materials such aluminum or magnesium, whereas the overall component requires more ductile material for toughness during service life. The inventive method of metallurgically bonded tailored surface on a tough substrate offers a wide array of choices for designers.

Temperature rise during operation is one of the reasons for distortion of the die. Asymmetric thermal loading and resultant stress distribution and thermal fatigue may also contribute to failure. The operating life of a component will increase with proper thermal management of the component. Moreover, carefully designed conformal cooling channels and heat sinks in a mold will substantially reduce the cycle time of the component leading to increased profitability for the users of "custom designed dies."

Lightweight materials, such as aluminum, are preferred for components for energy conservation, ease of die change, and improved thermal conductivity, but they often have poor wear resistance. A composite design with thin hard surface and lighter interior will satisfy both energy conservation and increased service life due to reduced surface wear.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGURE 1 is a schematic of a closed-loop, direct metal deposition system which includes the novel feedback controller and a CAD/CAM system for automated production customized die inserts and other parts according to the invention;

FIGURE 2 is a schematic view of a laser spray nozzle forming a melt-pool on a substrate article;

FIGURE 3 shows a schematic of a direct metal deposition system including a feedback control device;

FIGURE 4 shows a cast aluminum-silicon substrate with a metallurgically bonded Mo alloy working surface with nickel alloy bond coat for improved service life for die casting of low melting point materials such as Zn alloys; and

FIGURE 5 shows how a steel working surface is used in conjunction with an aluminum substrate, preferably further incorporating conformal cooling channels or highly conductive heat sinks such as copper or aluminum-clad graphite.

DETAILED DESCRIPTION OF THE INVENTION

According to the invention, closed-loop DMD (CLDMD) is used to deposit desired alloys on an existing surface of a die or a three-dimensional component utilizing the tool path generated by a suitable CAD/CAM package. Figure 1 is a schematic of a direct metal deposition system 102 which includes a novel feedback controller 104 of the invention and a CAD/CAM system 106 for automated production of parts. The factors considered to affect the dimensions of material deposition, include laser power, beam diameter, temporal and spatial distribution of the beam, interaction time, and powder flow rate. Among such factors adequate monitoring and control of laser power has a critical effect on the ability to fabricate completed parts within control tolerances. Accordingly, the feedback controller 104 of the invention preferably cooperates directly with the numerical controller (NC) 108 which, itself, controls all functions of the system, including laser power.

Continuing the reference to Figure 1, the system comprises a laser source 110 having an appropriate beam focusing means 112. The laser source is mounted above the substrate or workpiece in order to focus the beam thereon. The workpiece substrate is carried on the work table, though any of a number of variety of arrangements may be used to cause relative movement between the workpiece substrate and the laser spray nozzle. The system also includes a work table 114, power supply 116 and chiller 118 to cool the laser. It is preferred that the laser source be a continuous-wave or pulse $C0_2$, YAG, or any other wavelength laser having a power density enough to melt the material to be deposited. Typically, an RF-excited laser or high-power $C0_2$ laser is used. Preferably, the laser beam is directed roughly perpendicular to the surface of the substrate workpiece.

As shown in Figures 2 and 3, the system includes a nozzle assembly 202 which operates on the workpiece to apply a cladding layer by injecting powdered metal into the beam. Laser and nozzle assemblies of this kind are described in U.S. Patent Nos. 5,241,419 (Pratt, et al); 5,453,329 (Everett, et al); and 5,477,026 (Buongiomo). A suitable laser spray nozzle is available from Quantum Laser Corporation of Norcross, Georgia, and is as described in U.S. Patent No. 4,724,299.

The spray nozzle provides a common outlet for the beam and the powder so that both are consistently directed at the same point on the workpiece substrate. In a preferred configuration, the laser spray nozzle assembly includes a nozzle body with first and second spaced-apart end portions, as described in U.S. Patent No. 4,724,299. A beam passageway extends between the end portions and permits a laser beam to pass therethrough. A housing which surrounds the second end portion is spaced from the second end portion so as to form an annular passage. The housing has an opening coaxial with the beam passageway for permitting the laser beam to pass therethrough. A cladding powder supply system is operably associated with the passage for supplying cladding powder thereto so that the powder exits the opening coaxial with the beam.

The laser spray nozzle of the invention achieves uniform clad composition because the beam exits the nozzle substantially coaxially with the cladding powder, both

having the same focal point. The nozzle has a common outlet for the beam and the power so that both are consistently directed at the same point on the article. In this way, a common focal point is achieved which assures uniform clad composition. Similar results can also be obtained by side injection nozzle, however, side injection nozzle restricts the direction of clad movement whereas a concentric nozzle will allow change of direction of deposition at any instant.

Conventional laser cladding techniques move the metal article relative to the beam focal point through the use of jigs, parts handlers and the like. The beam focal point therefore remains fixed in space, as does the position of the injected powder metal stream. Uniform movement of the metal article usually requires a complicated jig which is difficult to manufacture, often expensive and frequently not very successful, particularly with extremely intricate geometries. For this reason, laser cladding of metal parts having intricate geometries has been difficult to achieve on a consistently uniform basis. Robots have become a standard piece of operating equipment in many metalworking plants. The typical robot has a wrist with five degrees of freedom, each of which can move with constant velocity. The robot may be powered electrically, hydraulically or pneumatically, or through some combination of these means. Utilization of a robot in conjunction with a laser cladding system helps toward means for achieving a uniform clad. The article may remain fixed in space and the nozzle may therefore move relative to the article in cooperation with movement of the robot arm. Alternatively, the nozzle may remain fixed and the article moved by the robot.

The numerical controller 108 preferably controls all operating components of the assembly of Figure 1, including the conditions of operation of the laser, accepting direction from the CAD/CAM computer 106 for building the article, part or workpiece. The NC controller also receives feedback control signals from the feedback controller to adjust laser power output, and further controlling the relative position of the work table and the laser spray nozzle assembly. A numerical controller such as that utilized in Figure 1 is obtainable from a number of vendors including FANUC, Allen Bradley, IGM, etc. The CAD/CAM system is of a conventional type and may comprise a work station

supplied by any commercial vendor such as Sun Microsystems, Silicon Graphics, or Hewlett Packard. Among the features required of the CAD/CAM software is its ability to generate a path across the substrate for material deposition. This makes is possible to execute rapid prototyping and form a solid three-dimensional object directly from CAD dimensions, including the production of direct metal prototypes utilizing the laser spray nozzle.

As best seen in Figures 2 and 3, the laser spray nozzle 202 forms a melt-pool 204 on a substrate article 206. Powder is preferably injected through a nozzle 208 around the laser beam 204. It is preferred that the laser beam projection on the substrate surface not be Gaussian profile. It is preferred that the laser beam projection be of a relatively general doughnut shape with maximum intensity occurring peripherally. Thus, in contrast to a Gaussian profile, the midpoint of the beam profile has a lower intensity. This provides a melt-pool of relatively uniform temperature distribution. However, other spatial distributions of the laser beam can be adapted for the process.

Figure 3 shows a schematic of a direct metal deposition system including a feedback control device 302. The energy delivered from the laser is shown by a large arrow, and a small arrow shows powder being delivered into the powder delivery system. Chilled water 306 is shown being delivered to the outlet of the laser spray nozzle. The feedback unit 302 is preferably disposed directly adjacent to the point where the laser and powder are incident on the surface of the workpiece 310.

For reconfiguration of the surface profile to satisfy a completely new design, or to change an existing design, the required area on the object can either be machined off to a desired shape and subsequently built up using CLDMD directly from the new CAD data, or built over the existing surface, if the new design can accommodate it. With proper selection of the deposit alloy system a functional component can be designed and fabricated with tailored properties such as improved service life during die casting within the limitation of the available alloy systems. The strategy for surface modification to the tailored surface is as follows:

Selection of Phases

A face-centered cubic (F.C.C) structure with a large number of available slip planes is beneficial for ductility, whereas more brittle non-cubic phases with a limited number of available slip planes will promote hardness and wear resistance. A combination with duplex phases is often beneficial for providing adequate toughness during service with reasonable wear resistance.

Selection of Elements

The selection of elements is important in promoting certain phases as well as protection against chemical degradation. For example, elements such as molybdenum have very little solubility in aluminum. Exposed die surfaces with metallurgically bonded Mo alloys therefore improves the service life of die casting by maintaining the surface integrity.

Selection of Process Parameters

Process parameters control the cooling rate, which controls phase transformation kinetics. As such, process parameters are carefully selected to promote the desired phases. Inherent high cooling rate and strong convection associated with laser melting and solidification of CLDMD promotes atom trapping leading to extended solid solution. These non-equilibrium syntheses are utilized to dissolve low solubility material such as Y and Hf.

The capability of non-equilibrium synthesis of CLDMD may also be utilized to fabricate lightweight tools. In particular, a light material such as aluminum may be used as substrate, with a wear-resistant or high-temperature material being deposited with a desired geometry and properties for the working surface. For example, as shown in Figure 4, in one embodiment, a cast aluminum-silicon substrate 302 uses a metallurgically bonded Mo alloy working surface 304 with nickel alloy bond 306 coat for improved service life for die casting of low melting point materials such as Zn alloys. The metallurgical bond will also provide enhanced heat extraction. Although a nickel alloy is used this example, any alloys which are miscible to both the substrate and the